Isolated Refuges for Surviving Global Catastrophes

Seth D. Baum[1,2], David C. Denkenberger[1], Jacob Haqq-Misra[1,2]
1. Global Catastrophic Risk Institute, http://gcri.org
2. Blue Marble Space Institute of Science, http://bmsis.org

Futures 72: 45-56. This version 14 October 2015.

Abstract
A variety of global catastrophes threaten the survival of human civilization. For many of these catastrophes, isolated refuges could keep some people alive and enable them to rebuild civilization in the post-catastrophe world. This paper examines the potential importance of refuges and what it would take to make them succeed. The successful refuge will have a variety of qualities, including isolation from catastrophes and self-sufficiency. These qualities can be achieved through a variety of specific design features. We introduce the concept of surface-independence as the gold standard for refuge excellence: refuges isolated from Earth's surface will offer maximum protection against both the catastrophe itself and potentially harmful post-catastrophe populations. However, surface-independence introduces significant design challenges. We present several challenges and evaluate possible solutions. Self-sufficiency in food provision can be greatly enhanced via chemical food synthesis. The rejection of waste heat from subterranean refuges can be enhanced via building piping networks and locating refuges near running groundwater or in ice. The high cost of extraterrestrial refuges can be offset by integrating refuges into space missions with scientific, political, or commercial goals. Overall, refuges show much promise for protecting civilization against global catastrophes and thus warrant serious consideration.

Keywords: catastrophic threats; global catastrophic risk; refuges; surface-independence

1. Introduction

From the perspective of the long-term success of human civilization, a global catastrophe could be a crucial event. A sufficiently severe catastrophe could cause total human extinction, in which case civilization will have no long-term success. Or, a catastrophe could leave some survivors, but the survivors are unable to maintain or rebuild the sophisticated civilization of the pre-catastrophe population, and again there will be no long-term success, or at least no significant long-term success. The stakes here are very high. Absent such a catastrophe, civilization could continue to flourish on Earth for about one to five billion years and in the rest of the universe for much longer; it also has a variety of technological options for scaling up its sophistication. The enormous potential for human civilization provides strong reason to protect it against global catastrophes.[1]

One proposed response to global catastrophes is for pre-catastrophe populations to build and maintain refuges that enable small populations to survive global catastrophes and rebuild civilization. A small but growing literature develops the refuges proposal. Hanson (2008) proposes the idea and explores how selling refuge access could be used to infer catastrophe probabilities: access prices would increase when people felt catastrophes were more imminent. Abrams et al. (2007) and Shapiro (2009) propose a staffed data backup facility on the moon to

[1] For further discussion of the importance of protecting against global catastrophes, see e.g. Ng (1991), Leslie (1996), Tonn (2002), Posner (2004), Beckstead (2013), Bostrom (2013).

keep civilization's population, knowledge, and cultural artifacts intact through catastrophes on Earth. Maher and Baum (2013) suggest refuge-like resource stockpiles to facilitate recovery from global catastrophes. Jebari (2014) developed the idea of refuges as a solution to potential unknown catastrophes. Beckstead (2014; 2015) surveys issues surrounding refuges and prior work on the topic and discusses refuge cost-effectiveness, finding that other interventions are likely more cost-effective for facilitating recovery from global catastrohes. All of these publications develop technical specifics of refuges in varying degrees of detail. This paper contributes to this literature by providing novel discussion of surface-independence for subterranean and extraterrestrial refuges.

Several other lines of work are relevant to this discussion of refuges. Some countries have built civil defense facilities to protect their citizens during war and facilities for leadership to preserve continuity of government (e.g., McCamley 2007). On a smaller scale, disaster response and recovery are ubiquitous throughout the world. Private citizen survivalists or "preppers" often create their own refuges for surviving a variety of catastrophes. Some religious communities such as the Mormons support this sort of catastrophe preparedness. Finally, work on space travel is also relevant, because spaceships and space stations must achieve a high degree of self-sufficiency at low population numbers.

This paper discusses the potential for pre-catastrophe populations to build and maintain refuges that enable small populations to survive global catastrophes and rebuild civilization. The paper contributes to the refuges literature original detail on practical aspects of refuge design, construction, maintenance, and use. A successful refuge would need to be able to withstand the shocks of the catastrophe, keep alive enough people to maintain a viable human population into future generations, and provide its population with the tools necessary to maintain or rebuild civilization. The successful refuge would also need to be either permanently occupied or sufficiently accessible that occupants can reach it before the effects of the catastrophe prevent them.

If successful refuges can be built, they would give long-term human civilization some hope in the face of many of the worst catastrophe scenarios, including nuclear winter, pandemics, contagious biological weapon use, asteroid impacts, volcano eruptions, and geoengineering failure. Indeed, a core advantage of refuges is that they can help across a wide range of global catastrophes, potentially including catastrophes that have not yet been imagined. A civilization intent on ensuring its long-term survival would be wise to consider building and maintaining refuges.

Ideally, such catastrophes would not occur in the first place, and refuges would be irrelevant. Likewise, building and maintaining refuges does not make it unimportant to try preventing catastrophes. One reason is that the success of the refuge and its survivor population is not guaranteed—refuges can increase the probability of post-catastrophe civilization existing, but they do not make the probability 100%. Another reason is that a catastrophe could diminish civilization's long-term success even if there is a post-catastrophe civilization. Indeed, the survivor population could be small and slow to rebuild. Finally, even if civilization would go on to have the same long-term success, it would still suffer the short-term harms of the catastrophe itself. And so, even with refuges in place, it will remain worthwhile to try preventing catastrophes. For comparison, a good helmet can protect a cyclist from fatal injury, but she should still try to avoid crashing in the first place.

Figure 1 sketches the potential values of refuges and of avoiding catastrophe in the first place. The figure shows civilization wellbeing as a function of time. Civilization wellbeing could be a function of population, per capita quality of life, and/or other measures. The curves show various possible trajectories for civilization. The baseline trajectory depicts civilization avoiding catastrophe and gradually growing in wellbeing over time. The catastrophe causes an abrupt decline in wellbeing. In the absence of a refuge, extinction occurs. (Note, not all relevant catastrophes would result in extinction absent a refuge.) The refuge keeps a small population alive. Absent recovery, this population continues at roughly the same low level of wellbeing. Finally, the figure shows two recovery scenarios, one with the same long-term success as the baseline case and one with diminished long-term success.

The values of refuges and of avoiding catastrophe can be obtained from integrating the Figure 1 trajectories over time. The baseline trajectory has the highest value, followed by, in order, recovery with same long-term success, recovery with diminished long-term success, survival without recovery, and extinction. The grey shaded areas show the difference in value between adjacent trajectories. The light grey area shows the value of avoiding catastrophe if the same long-term success would follow. This area is large but finite, whereas the dark grey area extends into the distant future and thus is much larger. The dark grey area shows the additional value lost if civilization ends up with diminished long-term success relative to the baseline trajectory.

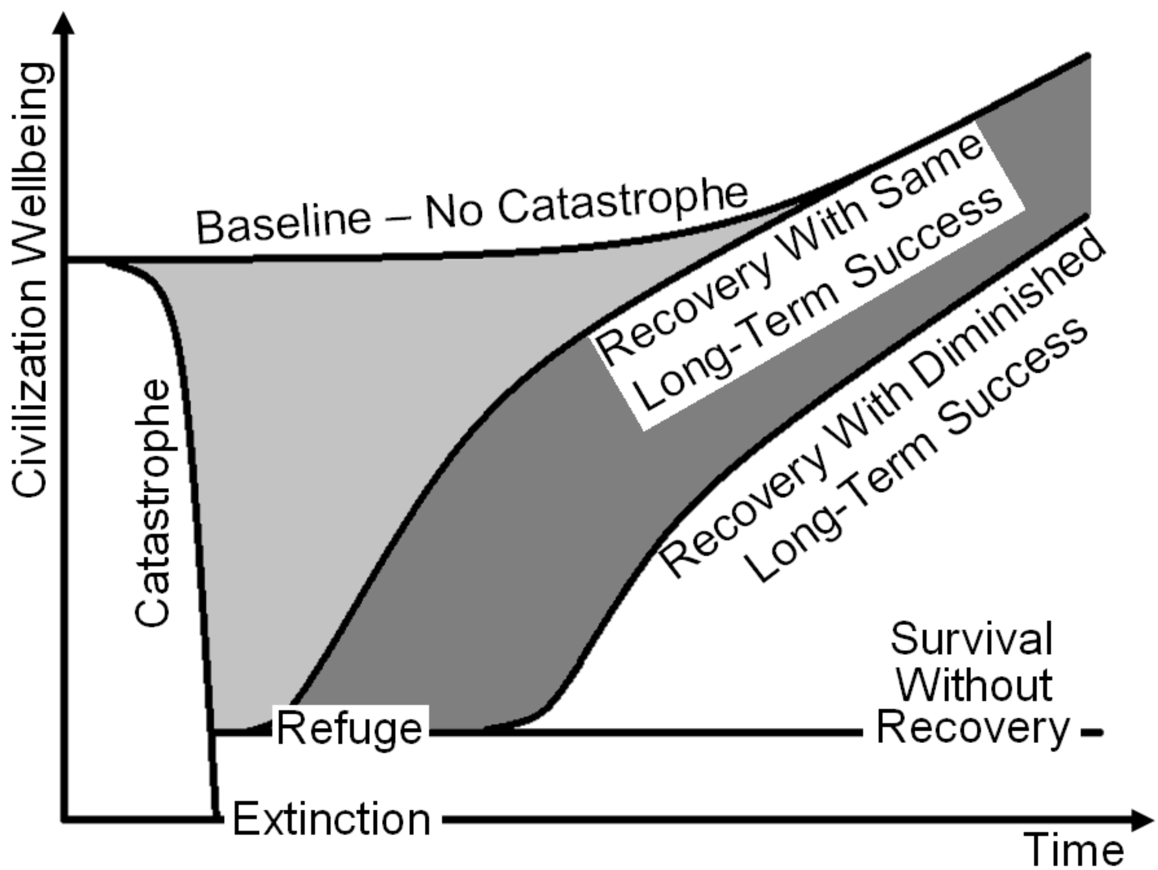

Figure 1: Trajectories of civilization wellbeing under baseline (no catastrophe) scenario and several catastrophe scenarios. No fixed time scale is intended for the horizontal axis, as catastrophe scenarios could play out over a variety of time scales.

A few basic insights follow from Figure 1. First, even if the same long-term success would occur, there is still a significant value in avoiding catastrophes (the light grey area), though this value is small relative to anything that affects the long-term success of civilization. Second, in the (perhaps likely) event that long-term success would be diminished following catastrophe, there is very large value in avoiding catastrophes (the light and dark grey areas combined). Third, if refuges can avoid extinction, then it is especially important for them to also enable recovery, even with diminished success (the added value being the white area to the right of the dark grey area). These basic insights should inform refuge design. Above all, any refuge that could shift post-catastrophe outcomes away from extinction and towards recovery with greater long-term success would be of very high value to human civilization.

With these insights in mind, the remainder of the paper focuses on practical matters of refuge design, construction, maintenance, and use. We aim to inform several questions: What would a successful refuge look like? Where would it be located? What design features would it include? What tradeoffs exist between the success of a refuge in terms of protection against catastrophes vs. other criteria such as cost and ease of use? What existing projects could it have synergies with? And above all, what would it take to make the refuge a reality?

The paper is organized as follows. Section 2 surveys the various scenarios that refuges could provide some degree of protection against. The breadth of relevant scenarios further indicates the potential importance of refuges and also suggests some important design features. Section 3 takes a closer look at what qualities can make a refuge more successful at keeping people alive and well through catastrophes and enabling civilization recovery. Section 4 introduces the concept of surface-independence as an important design feature for refuges. Sections 5-7 present options to address important design challenges for surface-independent refuges. Section 5 discusses design options for food provision, highlighting the merits of chemical food synthesis. Section 6 discusses design options for waste heat rejection in subterranean refuges, examining prospects for building piping networks or locating refuges near groundwater or in ice. Section 7 discusses options to offset the high cost of extraterrestrial refuges, discussing synergies between refuges and space missions planned for other purposes. Section 8 concludes.

2. Relevant Catastrophe Scenarios

As mentioned above, refuges can help keep some people alive through a variety of catastrophe scenarios. It is worth surveying these scenarios in some depth to show just how broadly useful refuges can be in protecting against catastrophes, and to illustrate the sorts of qualities and features that a successful refuge will need. The following list covers a significant range of relevant catastrophe scenarios but is not intended to be comprehensive.

Nuclear winter. A sufficiently large nuclear war would send smoke from the explosions and resulting fires into the stratosphere, blocking sunlight, which reduces surface temperatures and precipitation (Mills et al. 2014). These effects could cause widespread agriculture failure for a time period on the order of five to twenty years. The probability of nuclear winter is difficult to quantify, but one study finds one specific nuclear war scenario (Russia-United States war initiated by a false alarm misinterpreted as a real attack) to have a probability in the range of approximately once per 100 to 10,000 years (Barrett et al. 2013); the total probability across all nuclear war scenarios would be larger than this.

Impact events. An impact with a sufficiently large asteroid or comet would send dust into the stratosphere, with effects similar to nuclear winter (Bucknam and Gold 2008). The upper limit of the severity of catastrophe is significantly higher for impact events than for nuclear winter, though the probabilities are also much lower for asteroid or comet impacts, around once every 100,000 to 10,000,000 years (Toon et al. 1997). A 100 km diameter impactor would boil the oceans and would take thousands of years for the atmosphere to cool off (Sleep and Zahnle 1998). Furthermore, the added mass of the oceans as vapor in the atmosphere would increase the pressure of the atmosphere by hundreds of times the present value. This high pressure environment and long catastrophe duration make the refuge significantly more difficult to design; the designs considered here would mainly be relevant to smaller, more probable impact events.

Supervolcano eruption. A sufficiently large volcano eruption, such as Yellowstone, could send large quantities of sulfur dioxide into the stratosphere, blocking incoming sunlight, with effects similar to nuclear winter and asteroid impact. Some have speculated that the Toba eruption 74,000 years ago almost caused human extinction, though recent archaeological evidence questions this hypothesis (Petraglia et al. 2007). As with impact events, the probabilities of supervolcano eruptions are low relative to nuclear winter, estimated at around once every 50,000 years (Rampino 2002).

Human pandemic. A highly contagious and lethal disease could kill a large portion of the human population. Death rates could even approach 100%, especially if the pathogen is specifically engineered to be so lethal. While developing bioweapons is more difficult than sometimes believed (Ouagrham-Gormley 2013), the risk remains significant and is expected to increase as biotechnology improves.

Geoengineering failure. Geoengineering is the intentional manipulation of the global Earth system, typically to lower temperatures in response to global warming (Caldeira et al. 2013). One prominent form of geoengineering involves injecting particles into the stratosphere to block incoming sunlight. This geoengineering could fail catastrophically if humanity stops injecting particles into the stratosphere, causing temperatures to rapidly warm. Of particular concern are “double catastrophe” scenarios in which the particle injection stoppage is triggered by another catastrophe, such as some of the other catastrophes considered here (Baum et al. 2013).

Crop pandemic. A pathogen that takes out even a single major crop would be catastrophic. In the context of bioengineering and biological warfare or terrorism, it is conceivable that pathogens could simultaneously target several or even all major crops. Biological weapons have targeted crops and livestock repeatedly throughout human history (Dudley and Woodford 2002) and could happen again.

Systemic failure. Modern global civilization is tightly interconnected, prompting concerns that a smaller catastrophe could ripple throughout, causing global catastrophe. Similar systemic failures have been observed at regional scales, such as the 2003 Italy blackout (Buldyrev et al. 2010). As critical systems fail, civilization may be unable to cope and could collapse.

Nanotechnology catastrophe. Though the threat of self-replicating nanotechnology may be smaller than previously thought (Drexler 2013), it is not negligible. Also, molecular manufacturing could create very powerful weapons, or larger numbers of less powerful weapons. This is due to the general capacity of molecular manufacturing to make manufacturing less expensive and more widely available.[2] A refuge would allow time to possibly overcome some of these threats.

Artificial intelligence (AI) accident. Some scholars are concerned about the potential for certain types of AI to cause global catastrophe (Eden et al. 2012). For some of these AI, a refuge

[2] Drexler (2013) argues that molecular manufacturing could decrease military risks, but this depends on how the technology is used.

may offer no protection, as the AI would find or otherwise destroy the refuge. However, there may be other globally catastrophic AI for which refuges offer some protection, such as AI that destroys computer systems and crashes the economy, or AI that self-destructs after causing significant but not total damage.

Unknown threats. Refuges are broadly useful for catastrophes that cause rapid death of the human population, but do not destroy the entire planet and do not have effects that linger for long times. This could include a variety of threats not yet identified, making refuges an attractive option for an uncertain future (Jebari 2014).

There are some types of catastrophe scenarios for which refuges would be less helpful. One type is catastrophes that destroy the entire planet, which could include certain AI and high energy physics experiment accidents. Any refuge on Earth would also be destroyed, and potentially refuges in space would be too. Another type is catastrophes that have effects that linger for long times, which could include certain human or crop pandemics. Survivors could be exposed to these effects upon exiting the refuge, denying them the opportunity to rebuild civilization. A third type is catastrophes that progress slowly, which could include a variety of ecological catastrophes (Rockström et al. 2009). Refuges could need to protect their residents throughout the long duration of these catastrophes, which makes the refuge design challenge considerably more difficult.

3. Refuge Design Qualities

In light of the preceding discussion of catastrophe scenarios, here are some general qualities that will be important to include in refuge design in order to keep its inhabitants alive and well during the catastrophe and able to rebuild civilization afterwards. Successful refuges could achieve these qualities using a variety of specific design features. Other refuge design qualities may also be important, but we believe this list to be a good starting point covering a range of crucial qualities.

Isolation. Refuges need to be isolated from the cause of the catastrophe, such as nuclear weapon detonations or a pathogen. Refuges may also need to be isolated from the greater post-catastrophe population, which could include many desperate and aggressive people—the "golden hordes" of prepper lore (Anonymous 2012). While these people could potentially benefit from refuge supplies, their presence could also bring infection, chaos, or other threats to the long-term success of the refuge and in turn human civilization. In short, the refuge should be prepared to follow lifeboat ethics (Hardin 1974). Refuges may thus be more successful if built some distance away from major cities, and with sealed and fortified walls. Refuges should also be constructed in geologically inactive areas (e.g., away from fault lines, flood plains, regions prone to seasonal disasters, and volcanic hot spots) to minimize maintenance needs.

Secrecy. Similarly, a secret refuge is more likely to avoid being discovered by post-catastrophe outsider populations, increasing its probability of success. If secrecy would reduce the overall probability of success, for example if refuge resources would be sufficiently beneficial to outsiders, then insiders could simply reveal their location. Secrecy could sometimes be unnecessary, especially for highly isolated refuges. For example, post-catastrophe outsiders could probably not access a refuge on the moon or in other extraterrestrial locations, even if they had full knowledge of it. Finally, the advantages of secrecy must be balanced against downsides such as making it harder to recruit inhabitant populations.

Self-sufficiency. An isolated refuge will not be able to trade with the outside world. Depending on how sealed off the refuge is, it may not even be able to make basic physical exchanges with the surrounding environment. It thus may need to have a high degree of self-sufficiency in terms of food, water, air, temperature, other basic needs, and potentially other factors as well.

Continuous population. It may be important for the refuge to be continuously populated during pre-catastrophe times, in order to ensure a suitable population present in the refuge whenever catastrophe strikes. The need for continuous population is especially important if catastrophes can occur at unpredictable times and have effects that spread around the globe faster than the refuge can be reached.

Accessibility. Alternatively, if the refuge is not continuously populated, then it must be sufficiently accessible that its designated population can reach it after catastrophe strikes without bringing harm (e.g., pathogens) to the refuge.

Desirability. A refuge that nobody is willing to live in is unlikely to succeed. Interest in living in a refuge could skyrocket after catastrophe strikes, so emphasis should be placed on making the refuge desirable for continuous habitation during pre-catastrophe times. Efforts to make a refuge appear desirable must be balanced against needs for secrecy, as too much refuge marketing could reveal crucial refuge details.

Pleasantness. Similarly, a fixed population living in a confined space for an extended duration could suffer from a variety of psychological and social problems. Concerns about the catastrophe itself and the burden of surviving it and rebuilding civilization could take a further psychosocial toll. Refuges should thus be designed to offer a pleasant experience for inhabitants. A pleasant experience can also support the goal of desirability by ensuring that current inhabitants will desire to stay in the refuge or to return if habitation is structured in shifts.

Monitoring. While a refuge may benefit from being isolated from the outside world, it will still need to know what is going on outside. In particular, the refuge project will benefit from insiders knowing when a catastrophe hits, what type of catastrophe it is, what post-catastrophe conditions are like, and when it is safe to go outside.

Sufficient founder population. Refuge inhabitants could be the only catastrophe survivors, or the only survivors within an accessible distance. In order for civilization to recover and have long-term success, the refuge inhabitants will need to serve as a founder population for many future generations. The refuge population will thus need a sufficient size and diversity of people capable of producing successful offspring. Populations exceeding the bare minimum sufficient size and diversity may further be desirable towards improving the overall quality of the post-catastrophe population.

Resources for civilization. Similarly, achieving long-term civilization success may also benefit from the refuges containing certain resources, such as agricultural seeds, tools, and libraries of information. Some of the resources would only be used when inhabitants leave the refuge after a catastrophe. These resources might not need to be stored in the refuge itself, but potentially could be stored in an accessible nearby location.[3] The storage facility should itself be safe from catastrophes as well as pre- and post-catastrophe populations.

Cost. Finally, refuge cost is important because it affects the number and quality of refuges that can be built. Cost here can be in monetary terms as well as in terms of any other relevant resources.

4. Surface-Independence

[3] In contrast, the Svalbard seed vault (Fowler 2008) is an example of a storage facility that is unlikely to be accessible to refuge inhabitants or other post-catastrophe survivors.

Different refuge designs may achieve the qualities described in Section 3 to varying degrees of success. Looking across extant refuge designs, one key issue that we believe has not yet been adequately addressed is the technical challenge of maintaining self-sufficiency in a refuge with a high degree of isolation for an extended (multiple years or longer) period of time. For some catastrophe scenarios, being located at or even near Earth's surface may fail to provide sufficient isolation from both the catastrophe itself and desperate survivor populations. Less isolated, surface-dependent refuges can still provide some protection against some global catastrophes, and may even be more cost-effective in some circumstances. However, building refuges that are completely independent from Earth's surface would maximize prospects for refuge success, and in turn the long-term success of human civilization. Surface-independent refuges are the gold standard of refuge excellence.

There are three basic types of surface-independent refuges: subterranean, aquatic, and extraterrestrial. A subterranean refuge would be located sufficiently underground that it is not accessible from the surface, and is further built without significant connections to the surface. Jebari (2014) focuses on subterranean refuges. Most existing refuges are surface-dependent subterranean refuges. This includes public designs such as fallout shelters and continuity of government bunkers, as well as private designs from companies such as Radius Engineering[4] and Vivos.[5] New design work is needed to achieve surface-independent subterranean refuges.

An aquatic refuge would be located underwater. To our knowledge, the possibility of aquatic refuges has not received dedicated research attention, though Jebari (2014) does note similarities between refuges and submarines. Aquatic refuges could have certain advantages over subterranean refuges, especially regarding waste heat rejection (see Section 6). Dedicated treatment of aquatic refuges beyond the scope of this paper is warranted.

Finally, extraterrestrial refuges would be located in orbit or on another astronomical object. The moon and Mars are most commonly considered. Extraterrestrial refuges may be dependent on the surface of other astronomical objects. In terms of protection against global catastrophes, what matters is that they have surface-independence from Earth. Abrams et al. (2007) and Shapiro (2009) are among those considering extraterrestrial refuges, while Carl Sagan and others have called for full space colonies to protect against catastrophes on Earth (Sagan 1994).

We now turn to some significant design challenges for surface-independent refuges, and potential solutions to these challenges.

5. Food Provision

Surface-independent refuges will lack access to the usual terrestrial food markets that exist pre-catastrophe. Furthermore, post-catastrophe conditions may be too hazardous to permit refuge inhabitants to leave the refuge and resume hunting, gathering, or agriculture on Earth's surface. As a result, it is important for surface-independent refuges to be able to produce their own food. Three major food and air options are: (1) store enough food to feed refuge inhabitants for as long as necessary; (2) onsite food production through photosynthesis; and (3) onsite food production through chemical synthesis of food.

Food storage. Food storage is perhaps the simplest and most common means of food provision in refuges. Indeed, a first step for many basic refuges and other survival facilities is to stockpile food. However, food stockpiling creates a tradeoff between the size of the food storage space needed and the length of time the food will last for. For long-term habitation, refuges will

[4] http://undergroundshelters.com
[5] http://www.terravivos.com

greatly benefit from the ability to produce food onsite. Furthermore, food stockpiles do nothing for air quality; onsite food production, whether through photosynthesis or chemical synthesis, can remove carbon dioxide from the air. Surface independent refuges using food stockpiles will need separate means to prevent carbon dioxide concentrations from reaching dangerous levels.

Photosynthesis. For onsite food production, photosynthesis is perhaps the simplest option, or at least the most obvious. This just requires suitable lighting systems and plants or algae. For subterranean and aquatic refuges, and for some extraterrestrial refuges, it may not be possible to pipe enough sunlight in from the exterior, Photosynthesis would then require artificial light powered from whatever energy source is available. Specific plants can be selected or even engineered to maximize food quality (in terms of nutrition, taste, and any other factors) per unit energy and per unit volume, i.e. so that the most and best food can be produced for the least energy and using the least space in the refuge. In terms of food produced per unit energy, perhaps the most efficient option is to produce algae. The conversion of electricity to algae has an efficiency of about 2% (Denkenberger and Pearce 2014). However, factoring in electricity production, the overall thermal-to-food energy efficiency is only about 0.2%.[6]

Chemical synthesis. Chemical synthesis of sugars from non-carbohydrates has been feasible for decades (Hudlicky et al. 1996). Chemical synthesis of lipids and proteins may be similarly feasible. Minerals could be stored and vitamins could either be stored or synthesized. With 30% efficient conversion from electricity to food energy, the overall efficiency would be 3%, an order of magnitude greater than for photosynthesis. To the extent that chemical synthesis produces foods that are perceived as undesirable or are in practice unpleasant, these foods can be supplemented with onsite photosynthesis and/or food stockpiling. Indeed, perhaps the best arrangement involves a combination of all three food options, customized to the particular needs of the refuge.

Onsite food production, whether through photosynthesis or chemical synthesis, depends on onsite energy availability. Refuges would presumably have onsite energy production anyway, to power lighting and any other devices. The easiest energy options could involve fossil fuels or other combustibles. However, combustion produces smoke and other pollutants and requires oxygen, so this is not appropriate for a surface-independent refuge. Meanwhile, other energy options may offer more energy per unit volume, lessening the tradeoff between energy supply and energy storage space. Small-scale nuclear fission reactors might work. Another option is the radioisotope thermoelectric generator,[7] powered by radioactive decay, which has low efficiency but no moving parts and thus is highly durable. Steam and Stirling engines are more efficient, but have moving parts that would need to be maintained. The bottom line is that options are available to power subterranean refuges for extended periods of time.

6. Subterranean Waste Heat Rejection

Refuges, just like any other human settlement, produce heat. Heat is produced by the human bodies inhabiting the refuge as well as electricity and food production, among other things. More efficient energy and food production systems can reduce the quantity of waste heat to reject, but any system will produce some heat. This is basic thermodynamics at work, and it underscores the importance of designing refuges for thermal efficiency, such as by favoring chemical synthesis over photosynthesis for food provision.

---

6 We assume 10% efficient electrical production because of the relatively small scale of refuge power plants; this is lower than conventional large-scale power plants.

7 The electrical generator could also be thermionic (electrons or ions emitted because of high temperature) and thermophotovoltaic (similar to solar cells, but driven by infrared radiation from a hot surface).

For refuges on the surface, heat production is easy to manage because any excess waste heat can be rejected into the surrounding environment, which would then dissipate away. Aquatic refuges would also be able to easily dissipate heat into the surrounding water. Refuges on planets would generally have an atmosphere to which they can reject waste heat. A refuge in space or the moon would not have a gas or liquid to reject heat into, but radiators can be used similar to those in existing space stations. However, for subterranean refuges, the surrounding environment may not dissipate heat fast enough to maintain a comfortable thermal equilibrium inside the refuge. Dedicated design for waste heat rejection is thus warranted. Four major options for subterranean waste heat rejection are: (1) rejection at surface; (2) rejection into adjacent rock; (3) rejecting into groundwater; (4) locating the refuge in ice.

Rejection at surface. Rejecting heat at the surface of the earth may be the simplest to implement technically. Waste heat could be piped up to the surface and released. This approach is taken by common commercial refuges.[8] However, this surface-dependent design reduces refuge isolation, and potentially even requires refuges to be built closer to the surface. This negates a core reason for building a subterranean refuge in the first place.

Rejection into adjacent rock. For deeper refuges, the simplest option may be to reject heat into the adjacent rock. This would permit refuges to be located anywhere underground that is sufficiently cool, e.g. not near magma chambers. However, rock is a poor thermal conductor, meaning that it would not accept much heat from the refuge. Without dedicated design for waste heat rejection, the refuge gradually warms, eventually becoming uninhabitable. A design for rejecting more waste heat into adjacent rock could involve a network of piping drilled into the rock to reject heat into more of the rock. In principle, any amount of heat could potentially be rejected given a large enough piping network, but this comes at a cost. A tradeoff thus exists between the size of the piping network to drill vs. the thermal efficiency and operational duration of the refuge. A refuge that is less thermally efficient (i.e., gives off more heat) and that is operated for a longer period of time will require a larger piping network. Thus, certain investments in thermal efficiency and duration reduction may bring net savings by reducing piping expenditures for waste heat rejection. But reducing operational duration conflicts with the goal of continuous pre-catastrophe habitation and may also limit the range of catastrophes that the refuge can keep inhabitants alive for.

The need for waste heat rejection poses an additional constraint on subterranean refuges. Earth has a geothermal temperature gradient such that temperatures gradually increase at successively deeper points below the surface. Specifically, the temperature increases about 25°C per kilometer. Deeper refuges will need more waste heat rejection, because any given volume of rock starts out warmer and can accept less heat. Past a certain depth, rock becomes so warm that the energy required to reject heat to it would become prohibitive. This would render the refuge nonviable unless waste heat can be piped to higher elevations. For example, assuming a near-surface ground temperature of 10°C and a maximum permissible temperature of 35°C, then only the top 1 km of ground can accept heat from the refuge.

Rejection into groundwater. Options for waste heat rejection improve considerably if there is flowing groundwater nearby. Because the groundwater constantly cycles through, it provides a virtually unlimited capacity to accept waste heat. The main question becomes whether enough groundwater is available for the amount of heat the refuge needs to reject. Refuge design could include heat pumps to help transfer more heat from the refuge to the groundwater. However, the heat pumps will consume some of the refuge's electricity supply and will typically also have

[8] Vivos refuges also reject heat into adjacent rock.

moving parts that may require maintenance. Thermoelectric heat pumps do not have moving parts, though these are less efficient. It may also be possible to design electromagnetic pumps without moving parts if the conductivity of adjacent groundwater is sufficient. These are all important issues to consider in refuge design. That said, overall, locating refuges near flowing groundwater could significantly improve refuge cost and functionality.

Locating the refuge in ice. Perhaps the most exotic option for waste heat rejection would locate the refuge in ice. Refuges built inside glaciers would have very cold adjacent environments that could accept more heat with smaller piping networks. Some glaciers are at temperatures significantly below freezing and may be able to accept refuge heat without melting, especially with a sufficiently large piping network. In this case the thermodynamics would resemble that of rejection into adjacent rock, but with a much colder material. For warmer glaciers and smaller piping networks, some melting will occur, with thermodynamics resembling that of rejection into adjacent groundwater, especially if crevasses drained meltwater away. However, melting adjacent ice could cause the refuge to shift within the glacier, potentially affecting the refuge's functionality. Sufficient melting may even affect the glacier's structural integrity, potentially with catastrophic results for the refuge. Thus care must be taken to ensure that refuges in ice can succeed. But if they can succeed, locating refuges in ice would significantly enhance waste heat rejection.

Some other aspects of ice-based refuges are worth considering. Glacial regions tend to be relatively isolated from human populations, further enhancing the refuge. On the other hand, this isolation, combined with the general inhospitality of glacial regions, could significantly increase refuge cost and decrease accessibility. Additionally, when refuge inhabitants leave following a catastrophe, they would have to make their way from the glacial region to somewhere more hospitable—though they may be near the Svalbard seed vault. Glacial refuges would thus need to include supplies necessary for inhabitants traveling large distances and potentially across significant bodies of water, such as from Antarctica to South America. For these reasons, it is likely better to locate subterranean refuges in rock, assuming the problem of waste heat rejection can be solved.

7. Extraterrestrial Refuge Cost

Extraterrestrial refuges may offer the highest degree of isolation from Earth's surface. The remoteness of space makes secrecy unnecessary and guarantees that the survivor population in space remains distant and unaffected by nearly any catastrophe on Earth. The feasibility of extraterrestrial refuges is suggested by achievements such as the Mir space station and the International Space Station, which have allowed astronauts to live continuously in space for up to a year or more. Space exploration agencies continue to research food synthesis, space medicine, efficient energy generation, air quality management, and waste recycling for the purpose of improving space infrastructure. These same technologies could allow for a completely surface-independent refuge in space.

Perhaps the main critique of extraterrestrial refuges has been their relatively high cost compared to refuges on Earth (Sandberg et al. 2008; Baum 2009). The cost is indeed quite high. If the only goal is to minimize the risk of global catastrophe, then extraterrestrial refuges are unlikely to be advantageous, at least until space technology significantly improves. However, not everyone is focused exclusively on minimizing global catastrophic risk. Extraterrestrial refuges have a major advantage over subterranean and aquatic refuges in that they are also desirable for other reasons, in particular science, politics, and commerce. Indeed, preliminary space colonization efforts are already under consideration or development for other reasons, such as to access extraterrestrial resources (i.e., commercial interests) or to follow the pioneering spirit (i.e. scientific and interests). Extraterrestrial refuges may be able to "piggyback" on these existing efforts, thereby solving the cost problem.

Extraterrestrial refuges could be constructed in a variety of locations, and piggyback opportunities can be found throughout. One option is to construct artificial space habitats in orbit around Earth. This could follow a similar model to existing orbiting space stations, allowing regular communication with Earth and periodic rotation of inhabitants. Existing space stations designs are too small to sustain a viable population, but the construction of a large enough facility to serve as a refuge is limited fundamentally by cost rather than technology. Space habitats can be placed in the gravitationally stable orbital locations that exist between any two orbiting bodies, known as "Lagrange points". The "L5 Society" was founded in 1975 to promote the ideas of building space colonies at a stable Lagrange point in the Earth-moon system that would drift in a stationary orbit with a minimal expenditure of fuel (Brandt-Erichsen 1994). The legacy of the L5 society continues in the modern development of space colony concepts by various researchers and organizations that suggests opportunities for piggybacking a refuge onto such designs.

The surface of the moon and other planets also provide locations for permanent refuge sites, with Mars being the leading planetary candidate. Lunar or planetary refuges have the advantage of solid ground for infrastructure, which means that a refuge could be one component of a much larger colony effort. Any attempt to colonize a location in space will automatically create an isolated population that could serve to mediate or repopulate after a catastrophe on Earth, which implies that any successful space colony will have many of the desirable traits of a refuge. Shapiro (2009) argues on this basis that humanity should strive to build a refuge (or "sanctuary") on the moon in order to provide a populated site for scientific research that also protects our population, knowledge, and cultural artifacts. The goal of such a settlement is "to create a functional fragment of our civilization in a secure location. This will not be a conventional settlement, however, but will more resemble a scientific base: staff will be rotated regularly so that work in the facility would involve a tour of service, rather than a change of life" (Shapiro 2009). The same considerations apply to Mars; it is not yet clear whether economic and political pressures will favor the construction of a lunar or Martian refuge (or neither, or elsewhere).

The high costs of locating the refuge on the moon or another planet may be offset by the scientific and political interest in establishing a permanently staffed base there. Manned lunar missions inspired previous generations, and contemporary interest in travel to Mars has been sparked by groups such as SpaceX, MarsOne, and the Inspiration Mars Foundation. This interest suggests that a Martian colony could become a reality sometime in the future, even without any separate push for a refuge from Earth catastrophes. These added benefits of lunar or planetary refuges create additional incentives that may lead to their construction prior to (or concurrent with) terrestrial refuges.[9]

Another option that can help offset the high cost of space exploration is to allow commercial interests in space resources to help establish space refuges. Asteroids host a wealth of precious metals including gold, platinum, osmium, iridium, and other materials of commercial value that could be extracted through extensions of existing technology (O'Leary 1977; Sonter 1997;

[9] Space refuges should not be considered as replacements for terrestrial refuges but instead could act to supplement a global system of refuges. Indeed, an isolated space refuge can help to coordinate among terrestrial refuges during and after a catastrophe to aid in recovery through remote communication (Abrams et al. 2007).

Kargel 1994). Asteroid mining ventures will have similar requirements to contemporary space stations in their need for a sustained habitable environment, so the development of asteroid mining stations could help to facilitate the establishment of a space refuge. While appealing to scientific and political interests can help (Abrams et al 2007; Shapiro 2009), asteroid mining provides one of the few ways in which investors can yield a profit within a lifetime, so perhaps the profits from this lucrative market could concurrently establish a refuge in space.

A different—and inexpensive—type of extraterrestrial refuge option is the deliberate launch of Earth artifacts into space. Artifact launch cannot preserve population but can provide a refuge of sorts to knowledge or artifacts. Spacecraft launched in orbit around Earth could preserve significant amounts of information that would otherwise be lost in a global catastrophe (Rose and Wright 2004), and even physical objects could be stored if desired. The purpose of such an artifact would be to insure our knowledge against survival by remaining in a stable orbit where it could someday be retrieved if needed. Archival artifacts could reside in Earth orbit, at stable Lagrange points, or even on the surface of planets. The most important consideration is the ease at which the artifact can be retrieved. If a catastrophe is severe enough, then the ability to retrieve such an artifact will be delayed until the survivors regain the capability for space travel. Given this, the best option may be to launch artifacts with a trajectory designed to someday return to Earth, perhaps after 100 years at a known location in the ocean or a desert. Establishing this "extraterrestrial time capsule" could ensure access to the critical information stored in the artifact even if space travel capabilities are destroyed from a global catastrophe.

In the more distant future, the Sun will gradually brighten and make Earth completely uninhabitable. The major type of photosynthesis will cease about half a billion years from now when carbon dioxide levels are drawn down to low levels, and photosynthesis will cease altogether in about a billion years (Caldeira and Kasting 1992). Only microorganisms in subsurface and high altitude environments can survive the following two billion years as Earth's surface warms (O'Malley-James et al. 2014). Humans may be able to withstand the changes through contained artificial structures, food synthesis, and efficient energy management—in other words, with technologies similar to those that could be used for refuges today. Five billion years from now the sun will expand into a red giant past the orbit of Earth and engulf our planet in a fiery death. This distant future may be less concerning than more immediate catastrophic risks, yet it is important to remember that space exploration can help to insure our species against destruction even past the lifetime of Earth.

8. Conclusion

A variety of threats could bring catastrophic destruction to much or all of human civilization. For many of these catastrophes, some humans could survive in isolated refuges. Refuge inhabitants would then have a chance to rebuild civilization in the post-catastrophe world. Refuges could even be the difference between the long-term success or failure of human civilization on Earth and beyond. For this reason, refuges merit consideration within the broader landscape of possible responses to catastrophic threats to humanity.

For a refuge to successfully keep survivors alive through a major catastrophe, it may need to have a high degree of isolation from both the catastrophe itself and from potentially harmful post-catastrophe populations. To achieve this, the refuge may need to be located away from Earth's surface, in either a subterranean, extraterrestrial, or aquatic location, and have complete self-sufficiency in this location. While surface-based and surface-dependent refuges can help protect inhabitants through some catastrophe scenarios, surface-independence is the gold standard for refuge excellence. Surface-independence will typically be more expensive and less accessible, but it will provide maximum protection against a wider range of catastrophes.

Surface-independence also poses significant design challenges. However, the analysis in this paper indicates that these challenges will often have viable solutions, especially if one is willing to think outside the box. Food provision can be greatly enhanced with chemical food synthesis. Subterranean waste heat rejection can be achieved with piping networks or locating refuges near running groundwater or even in ice. The high cost of extraterrestrial refuges can be offset by appealing to scientific, political, and commercial interests. This is not an exhaustive list of challenges, but it does offer hope that high-quality surface-independent refuges can be achieved.

This paper is but another small contribution to the small but growing literature on refuges for surviving global catastrophes. Actual design and construction of refuges will need much more research. At this early point, several topics stand out as worthy of further research. Subterranean and extraterrestrial refuge designs must be fleshed out in greater detail. Aquatic refuge design has received virtually no attention and could be the subject of a dedicated analysis. The benefits of surface-independence should be compared to the costs as compared to surface-dependent refuges, and as compared to other means of protecting against catastrophic threats, including means of preventing catastrophes from happening in the first place. Finally, the entire refuges literature would benefit from dedicated attention to the prospects for refuge inhabitants in post-catastrophe environments, and in particular what steps can be taken now, in the pre-catastrophe world, to help ensure their success at rebuilding human civilization. For the sake of the long-term success of human civilization, this is a worthy project.

Acknowledgments
We thank two anonymous reviewers for helpful comments on an earlier version of this paper.

References

Abrams. S. et al., 2007. Phoenix: Final Report. International Space University, Strasbourg, France.

Anonymous, 2012. What is the Golden Horde? PreppingToSurvive.com, http://preppingtosurvive.com/2012/10/30/what-is-the-golden-horde

Barrett, A.M., Baum, S.D., Hostetler, K.R., 2013. Analyzing and reducing the risks of inadvertent nuclear war between the United States and Russia. Science & Global Security, 21(2), 106-133.

Baum, S.D., 2009. Cost–benefit analysis of space exploration: Some ethical considerations. Space Policy, 25(2), 75-80.

Baum, S.D., Maher, T.M. Jr., Haqq-Misra, J., 2013. Double catastrophe: intermittent stratospheric geoengineering induced by societal collapse. Environment, Systems and Decisions 33 (1), 168-180.

Beckstead, N., 2013. On The Overwhelming Importance Of Shaping The Far Future. Doctoral Dissertation, Department of Philosophy, Rutgers University.

Beckstead, N., 2014. Improving disaster shelters to increase the chances of recovery from a global catastrophe. Effective Altruism Blog, 19 February. http://www.effective-altruism.com/improving-disaster-shelters-to-increase-the-chances-of-recovery-from-a-global-catastrophe

Beckstead, N., 2015. How much could refuges help us recover from a global catastrophe? Futures, forthcoming, doi:10.1016/j.futures.2014.11.003.

Bostrom, N., 2013. Existential risk prevention as a global priority. Global Policy 4(1), 15–31.
Brandt-Erichsen, D., 1994. The L5 Society. Ad Astra. http://www.nss.org/settlement/L5news/L5history.htm
Bucknam, M., Gold, R., 2008. Asteroid threat? The problem of planetary defence. Survival 50(5), 141-156, doi:10.1080/00396330802456502.
Buldyrev, S.V., Parshani, R., Paul, G., Stanley, H.E., Havlin, S., 2010. Catastrophic cascade of failures in interdependent networks. Nature 464, 1025–1028.
Caldeira, K., & Kasting, J. F., 1992. The life span of the biosphere revisited. Nature 360(6406), 721-723. doi:10.1038/360721a0
Caldeira, K., Bala, G., Cao, L., 2013. The science of geoengineering. Annual Review of Earth and Planetary Sciences, 41, 231-256.
Denkenberger, D.C., Pearce, J.M., 2014. Feeding everyone: Solving the food crisis in event of global catastrophes that kill crops or obscure the sun. Futures, in press, doi:10.1016/j.futures.2014.11.008.
Drexler, K.E., 2013. Radical Abundance: How A Revolution In Nanotechnology Will Change Civilization. New York: PublicAffairs.
Dudley, J.P., Woodford, M.H., 2002. Bioweapons, biodiversity, and ecocide: Potential effects of biological weapons on biological diversity. BioScience 52(7), 583-592.
Eden, A.H., Moor, J.H., Soraker, J.H., Steinhart, E. (Eds.), 2012. Singularity Hypotheses. Springer, Berlin.
Fowler, C., 2008. The Svalbard seed vault and crop security. BioScience, 58(3), 190-191.
Hanson, R., 2008. Catastrophe, social collapse, and human extinction, in: Bostrom, N., Cirkovic, M. (Eds.), Global Catastrophic Risks, Oxford University Press, Oxford, pp. 363-377
Hardin, G., 1974. Lifeboat ethics. Psychology Today, September.
Hudlicky, T., Entwistle, D.A., Pitzer, K.K., Thorpe, A.J., 1996. Modern methods of monosaccharide synthesis from non-carbohydrate sources. Chemical Reviews 96(3), 1195-1220.
Jebari, K., 2014. Existential risks: Exploring a robust risk reduction. Science & Engineering Ethics, forthcoming, doi:10.1007/s11948-014-9559-3.
Kargel, J.S., 1994. Metalliferous asteroids as potential sources of precious metals. Journal of Geophysical Research 99(E10), 21129-21141.
Leslie, J., 1996. The End of the World: The Science and Ethics of Human Extinction. Routledge, London.
Maher, T.M. Jr., Baum, S.D., 2013. Adaptation to and recovery from global catastrophe. Sustainability 5(4), 1461-1479, doi:10.3390/su5041461.
McCamley, N., 2007. Cold War Secret Nuclear Bunkers. Pen and Sword, South Yorkshire.
Mills, M.J., Toon, O.B., Lee-Taylor, J., Robock, A., 2014. Multi-decadal global cooling and unprecedented ozone loss following a regional nuclear conflict. Earth's Future 2, 161-176, doi:10.1002/2013EF000205.
Ng, Y.-K., 1991. Should we be very cautious or extremely cautious on measures that may involve our destruction? Social Choice and Welfare, 8, 79-88.
O'Leary, B., 1977. Mining the Apollo and Amor asteroids. Science 197(4301), 363-366.
O'Malley-James, J.T., Cockell, C.S., Greaves, J.S., Raven, J.A., 2014. Swansong biospheres II: The final signs of life on terrestrial planets near the end of their habitable lifetimes. International Journal of Astrobiology 13(03), 229-243. doi:10.1017/S1473550413000426.

Ouagrham-Gormley, S.B., 2013. Dissuading biological weapons proliferation. Contemporary Security Policy 34(3), 473–500.
Petraglia, M., Korisettar, R., Boivin, N., Clarkson, C., Ditchfield, P., Jones, et al., 2007. Middle Paleolithic assemblages from the Indian subcontinent before and after the Toba super-eruption. Science, 317(5834), 114-116.
Posner, R., 2004. Catastrophe: Risk and Response. Oxford University Press, Oxford.
Rampino, M.R., 2002. Supereruptions as a threat to civilizations on Earth-like planets. Icarus, 156(2), 562-569.
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., et al., 2009. A safe operating space for humanity. Nature 461(7263), 472-475.
Rose, C., Wright, G., 2004. Inscribed matter as an energy-efficient means of communication with an extraterrestrial civilization. Nature 431(7004), 47-49, doi:10.1038/nature02884.
Sagan, C., 1994. Pale Blue Dot: A Vision of the Human Future in Space. Random House, New York.
Sandberg, A., Matheny, J.G., Ćirković, M.M., 2008. How can we reduce the risk of human extinction? Bulletin of the Atomic Scientists, 9 September, http://thebulletin.org/how-can-we-reduce-risk-human-extinction.
Shapiro, R., 2009. A new rationale for returning to the Moon? Protecting civilization with a sanctuary. Space Policy 25(1) 1-5
Sleep, N.H., Zahnle, K., 1998. Refugia from asteroid impacts on early Mars and the early Earth. Journal of Geophysical Research: Planets, 103(E12), 28529-28544.
Sonter, M.J., 1997. The technical and economic feasibility of mining the near-earth asteroids. Acta Astronautica 41(4) 637-647.
Tonn, B.E., 2002. Distant futures and the environment. Futures, 34, 117-132.
Toon, O.B., Zahnle, K., Morrison, D., Turco, R.P., Covey, C., 1997. Environmental perturbations caused by the impacts of asteroids and comets. Reviews of Geophysics, 35(1), 41-78.